Proceedings of 1995 American Control Conference, Seattle, WA; June 21-23, 1995; pp 924-928.

Filtering Micro-Manipulator Wrist Commands to Prevent Flexible Base Motion

David P. Magee and Wayne J. Book
George W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA

Abstract

This work examines control issues related to positioning a small articulating robot attached to a much larger, flexible manipulator. By shaping the joint position error with a finite impulse response filter, actuation torques can be found to maneuver the small robot with minimal residual vibration of its base. This paper develops a new filter form with the advantage of shorter delay times than current input shaping methods. Experimental results show the effectiveness of the new filtering technique to prevent vibration when used as part of a feedback control system.

I. Introduction

Nuclear waste restoration projects and various space applications require long-reach manipulators to perform desired tasks. Design considerations often stipulate light-weight members that are inherently flexible. The manipulator control system must therefore consider issues such as accurate end-point positioning, vibration control and robustness to system and environment uncertainty. The control problem becomes even more difficult when a small, articulating robot is attached to the end of the flexible manipulator and used to perform accurate maneuvers. The small robot's motion generates inertial forces that will excite the flexible behavior of the large, flexible manipulator. This paper attempts to filter the feedback joint commands to prevent vibration in the compliant manipulator.

The filtering algorithm resembles the input shaping method developed by Singer and Seering [4] for specific values of delay time. Singer and Seering showed the effectiveness of their filtering approach using a delay time of one-half the damped period of oscillation for a second-order system. By adding constraint equations, they increased the robustness of their method which resulted in more filter terms positioned at integer multiples of their delay value.

Singh and Vadali [5] analyzed the input shaping approach and showed that the method actually places zeros at the second-order poles of a flexible system. Therefore, the robustness constraint equations developed by Singer and Seering actually place multiple filter zeros at the modeled poles of the second-order system. Singh and Vadali also showed that the delay time used by Singer and Seering produces positive filter coefficients.

Rappole, Singer and Seering [2] later investigated negative filter coefficients by relaxing their original robustness constraints. They were able to find filter sequences that were much shorter than original sequences but the optimal solution process appears system specific and could be difficult to implement on varying parameter systems. Singhose, Singer and Seering [6] recently developed a look-up procedure for negative input shapers that offers more promise.

The effect of an input shaping filter on the ability to position a micro-manipulator on a flexible manipulator was investigated by Magee and Book [1]. They showed that the input shaping technique was effective as a prefilter but the long delay times associated with the slow dynamics of the large flexible manipulator would not permit teleoperated tasks. The stability of the feedback control system was also affected when a filter designed for the slowest mode of vibration was inside the feedback loop.

This paper presents a general filter form with shorter delay times than current input shaping techniques. Limiting cases for the delay time are also investigated to better understand the effect on the frequency response of the filter. The filter is then applied within a feedback control scheme to position an IBM wrist that is attached to the end of a long reach flexible manipulator named RALF. Experimental results compare link deflection measurements on the flexible manipulator for feedback control with and without filtering when the wrist's pitch joint is moved.

II. General Filtering Approach

2.1 Filter Development

Previous work [5] has shown that the input shaping method prevents residual vibration by placing filter zeros at the pole locations of the flexible system dynamics. If uncertainty exists in the model, then multiple zeros are placed near the pole locations to add robustness to the shaping method.

Using this pole-zero cancellation concept, a general filtering approach can be developed to cancel a pole at $s \equiv s_1 = \sigma_1 + j\omega_1$ with a real component σ_1 in the range $\sigma_1 \leq 0$ and a real component ω_1 in the range $0 < \omega_1$. Consider a general two-term, discrete-time filter of the form

$$F_2(z) = \frac{1 - z_1 z^{-1}}{1 - z_1} \qquad (1)$$

which contains a zero at $z = z_1$ and a pole at $z = 0$. With a denominator of $(1 - z_1)$, the DC gain value of the filter is automatically set to 1.

This discrete-time filter form can be transformed to the continuous s-domain with a substitution of $z = e^{sT}$ into Equation (1). The resulting two-term, continuous filter form is

$$F_2(s) = \frac{1 - e^{s_1 T} e^{-sT}}{1 - e^{s_1 T}} \qquad (2)$$

with zeros in the complex s-plane at

$$s = \sigma_1 + j\left(\frac{\omega_1 T + 2n\pi}{T}\right) \qquad (3)$$

where $n = 0, \pm 1, \pm 2, \ldots, \pm\infty$. It is readily apparent that this filter form places a zero at the pole location $s = s_1$ and that the cancellation is independent of the delay time T. The theoretical limiting cases on the delay time are discussed in Section 2.2 of this paper.

For real physical systems, the model describing the flexible behavior contains real valued coefficients so that any complex pole will always have a complex conjugate partner. This result from complex variable theory implies that the filter in Equation (2) must be used to cancel the complex conjugate pair of poles at

$$s = \sigma_1 \pm j\omega_1 \qquad (4)$$

The filter form that cancels a pair of complex conjugate poles can be written as

$$F(s) = \frac{(1 - e^{s_1 T} e^{-sT}) \cdot (1 - e^{s_1^* T} e^{-sT})}{(1 - e^{s_1 T}) \cdot (1 - e^{s_1^* T})} \qquad (5)$$

where `*` denotes the complex conjugate. This form of the filter is physically unrealizable because the coefficients are complex. However, it can be simplified to a general three-term filter of the form

$$F_3(s) = \frac{1 - 2\cos(\omega_1 T) e^{\sigma_1 T} e^{-sT} + e^{2\sigma_1 T} e^{-s2T}}{1 - 2\cos(\omega_1 T) e^{\sigma_1 T} + e^{2\sigma_1 T}} \qquad (6)$$

where the subscript `3` denotes the number of terms in the filter. A similar filter form was derived in the z-domain by Rattan and Feliu using Wiener filter theory for feedforward control of flexible arms [3].

One can show that the zeros of this general filter form are

$$s = \sigma_1 \pm j\left(\frac{\omega_1 T + 2n\pi}{T}\right) \qquad (7)$$

where $n = 0, \pm 1, \pm 2, \ldots, \pm\infty$. With the general filter in Equation (6), multiple zeros can be placed at pole locations by convolving several of the filters together. However, each filter does not require the same delay time so there are many possible filter forms.

2.2 Limiting Cases on Delay Time

The apparent ability of this general filtering method to allow arbitrary delay times is not without limitations. Two interesting cases are when the delay time goes to zero and to infinity. First, consider

$$\lim_{T \to 0} \frac{1 - 2\cos(\omega_1 T) e^{\sigma_1 T} e^{-sT} + e^{2\sigma_1 T} e^{-s2T}}{1 - 2\cos(\omega_1 T) e^{\sigma_1 T} + e^{2\sigma_1 T}} \qquad (8)$$

Simple substitution of zero for the delay time value into Equation (8) yields an undefined result. After several applications of L'Hopital's rule, the limit is found to be

$$\lim_{T \to 0} F_3(s) = \frac{s^2 - 2\sigma_1 s + \sigma_1^2 + \omega_1^2}{\sigma_1^2 + \omega_1^2} \qquad (9)$$

which is a polynomial in the complex variable s with only zeros at the desired pole locations given by Equation (4). The location of the filter zeros can also be verified by letting $T \to 0$ in Equation (7).

For lightly damped systems, this lower limit cannot be achieved because the magnitude of the filter's frequency response goes to infinity with increasing frequency. However for $T > 0$, the magnitude is bounded for all frequencies. To demonstrate this point, let $s \to j\omega$ in Equation (6) to yield

$$F_3(\omega) = \frac{1 - 2\cos(\omega_1 T) e^{\sigma_1 T} e^{-j\omega T} + e^{2\sigma_1 T} e^{-j2\omega T}}{1 - 2\cos(\omega_1 T) e^{\sigma_1 T} + e^{2\sigma_1 T}} \qquad (10)$$

The critical frequency values of $F_3(\omega)$ are found by differentiating Equation (10) with respect to ω and solving the characteristic equation given by

$$\sin(\omega T)\left[\cosh(\sigma_1 T)\cos(\omega_1 T) - \cos(\omega T)\right] = 0 \qquad (11)$$

for ω. The critical values are given by

$$\omega = \frac{n\pi}{T} \qquad (12)$$

and

$$\omega = \frac{\cos^{-1}\left[\cosh(\sigma_1 T)\cos(\omega_1 T + 2n\pi)\right]}{T} \qquad (13)$$

where $n = 0,\pm1,\pm2,\ldots,\pm\infty$. Notice in Equation (13) that the periodicity of the cosine function was used.

Using these frequency values and the second derivative test on Equation (10), the extreme values of frequency response magnitude can be found. For example, if values of $n = 0,\pm2,\pm4,\ldots,\pm\infty$ in Equation (12) are considered, the magnitude of Equation (10) is 1 and is a local maximum. If values of $n = \pm1,\pm3,\ldots,\pm\infty$ are used in Equation (10), the frequency response magnitude is

$$\left|F_3(\omega)\right| = \frac{1 + 2e^{\sigma_1 T}\cos(\omega_1 T) + e^{2\sigma_1 T}}{1 - 2e^{\sigma_1 T}\cos(\omega_1 T) + e^{2\sigma_1 T}} \qquad (14)$$

and is a local maximum or local minimum depending on the value of the delay time. Section 2.3 discusses the effect of different values of delay time on the magnitude of the frequency response.

The frequency values given by Equation (13) are more difficult to analyze. Since a frequency response is only valid for lightly damped systems, the frequency values given by Equation (13) are the approximate zeros of the filter for small values of $\sigma_1 T$. This result can be verified with the frequency values given in Equation (7) if $\varsigma_1 = 0$ (i.e. $\sigma_1 = 0$).

The other limiting case for the delay time is when $T \to \infty$. Consider

$$\lim_{T\to\infty} \frac{1 - 2\cos(\omega_1 T)e^{\sigma_1 T}e^{-sT} + e^{2\sigma_1 T}e^{-s2T}}{1 - 2\cos(\omega_1 T)e^{\sigma_1 T} + e^{2\sigma_1 T}} \qquad (15)$$

Careful study of the terms will show that the limit goes to 1 as $T \to \infty$ since $\sigma_1 \le 0$. However, this limit should never actually be reached because the filter will not prevent vibration. Also, if the filtering algorithm is implemented in a feedback control system, stability considerations will arise long before this theoretical limit is reached.

2.3 Special Cases for Delay Time

The input shapers with negative impulses [2,6] can be realized with the filter form in Equation (6). The cosine function in the second coefficient of the filter dictates the sign of that particular term. In fact, ranges for the delay time corresponding to the extreme values in the frequency response are related to this term. For $0 < T \le \frac{\pi}{2\omega_1}$, the magnitude of the filter's frequency response given by Equation (14) is a global maximum at the appropriate critical frequency values. When the delay time is in the range $\frac{\pi}{2\omega_1} < T < \frac{\pi}{\omega_1}$, Equation (14) represents the magnitude of a local maximum of the filter's frequency response at the appropriate critical frequency values.

At $T = \frac{\pi}{\omega_1}$, the frequency response is a global minimum and Equation (14) represents the magnitude of the frequency response at the zeros of the filter. For T in the range $\frac{\pi}{\omega_1} < T < \frac{3\pi}{2\omega_1}$, Equation (14) represents the local maximum of the filter's frequency response at the appropriate critical frequency values. In the range $\frac{3\pi}{2\omega_1} < T \le \frac{2\pi}{\omega_1}$, the magnitude specified by Equation (14) is once again a global maximum at the appropriate critical frequency values. This process periodically repeats itself as $T \to \infty$ until the magnitude is 1. It is worth noting that when the magnitude is only a local maximum (or at the one global minimum), the global maximum value is 1 and the critical frequency values are given by Equation (12) when $n = 0,\pm2,\pm4,\ldots,\pm\infty$.

The work by Singer and Seering [4] involved a filter form that contained a fixed delay time related to one-half multiples of a second-order system's period of oscillation. If a delay time value of $T = \frac{\pi}{2\omega_1}$ is substituted into Equation (6), then Singer's two term filter results. The number of filter terms in Equation (6) is reduced to two because the second coefficient is zero for this particular delay time value. The critical frequencies can also be found by substituting the delay time value into Equation (12) to get

$$\omega = 2n\omega_1 \qquad (16)$$

and Equation (13) to get

$$\omega = (2n+1)\omega_1 \qquad (17)$$

where $n = 0,\pm1,\pm2,\ldots,\pm\infty$. For this delay time value, Equation (16) represents the frequencies at which the frequency response is a maximum and Equation (17) gives the frequencies at which the frequency response is a minimum (i.e. the zeros). Substituting the correct frequency values into Equation (10) will show that the frequency response is bounded by 1.

Figure 1 verifies this special case with a frequency response comparison using Singer's delay time value. The solid line is the frequency response of the filter resulting from the limit as $T \to 0$ given by Equation (9). The dashed line is Equation (6) using

Singer's delay time value for a system with properties of $\varsigma = 0.1$ and $\omega_n = 2\pi \cdot 5$ r/s.

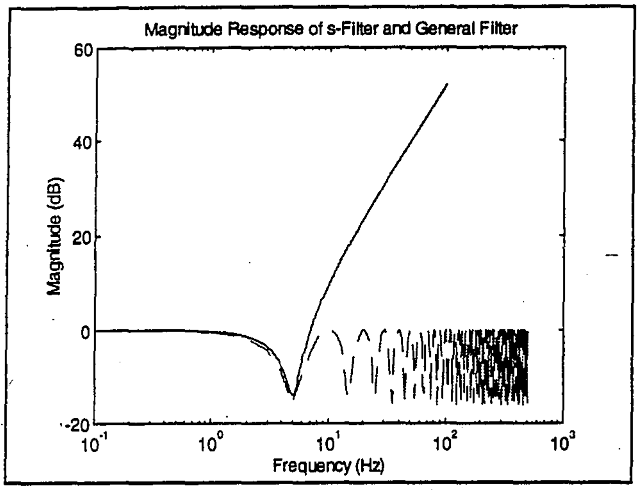

Figure 1. Frequency Response Comparison

III. Manipulator Testbed

The effectiveness of the general filtering method was tested using an IBM 7565 hydraulic robot wrist mounted on the tip of our two-link, flexible manipulator named RALF (Robotic Arm, Large and Flexible). The IBM wrist can be described kinematically with Roll-Pitch-Roll transformations and the axes are assumed to be principle directions to simplify the dynamics. Each link of RALF is a 10 ft. cylindrical aluminum beam. They are hydraulically actuated to move in a vertical plane. The frequencies of oscillation range from 3.7 Hz to 5.5 Hz for the first mode of vibration with damping ratios from 0.08 to 0.15.

Figure 2 shows the joint velocity and joint position feedback control system used to position each joint of the IBM wrist. This particular PD architecture using direct velocity feedback was chosen to give a step response with no overshoot. Notice that only the feedback error is filtered in this particular study without filtering of the velocity feedback signal. From experimental results, this filtering configuration gave the best response and permits the shortest filter delay times. Current work is to better understand the effect of the filtering strategy on the closed-loop poles and how various delay times influence the system response.

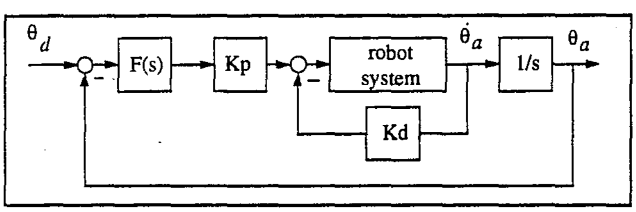

Figure 2. IBM Wrist Control System Block Diagram

The gains for each joint controller were determined from a model of the system without filtering in the feedback loop. Each joint was commanded to follow a 30 degree cycloidal trajectory with the other joints held in their home position. The time response criteria was a rise time of 0.1 seconds with minimal overshoot. However, the overshoot was not totally eliminated by the PD controller because the wrist is operating in a gravitational field.

A filter was then designed for RALF's first mode of vibration ($\varsigma = 0.15$ and $\omega_n = 2\pi \cdot 4.12$ r/s) in a configuration where both of its joints are at their maximum which is $\theta_1 = 110^\circ$ an $\theta_2 = 110^\circ$. A delay time of $T = \dfrac{\pi}{3\omega_1}$ produced a stable step response and Figure 3 shows the increase in the frequency response due to the shortened delay time. The solid line is once again the limiting case for the frequency response ($T \to 0$) and the dashed line is the frequency response of the filter for the given delay time. The maximum value of the frequency response is 9.4 dB and can be found using Equation (14). Notice that the magnitude is now greater than 1 since the delay time is 33% of Singer's value. By shortening the delay time, an amplification has been introduced within the feedback control system.

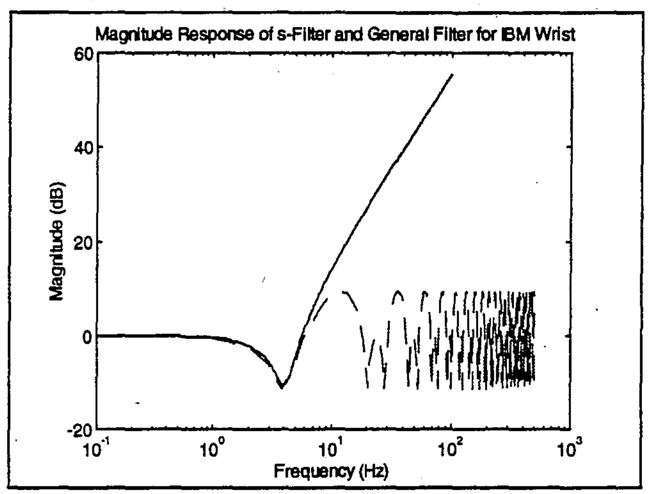

Figure 3. Frequency Response of Experimental Filter

IV. Experimental Results

The first experiment involves moving the pitch joint of the wrist from 30 degrees to 0 degrees while holding the first and second roll joints at 0 degrees. In this orientation, the wrist motion is in the vertical plane and will overshoot the desired position because of gravitational effects. However, the amplitude of vibration is reduced by almost 60% over conventional

PD joint control. Figure 4 shows the lateral deflection of RALF's upper link during the 30 degree slew of the pitch joint on the wrist. The amplitude of vibration is reduced to levels found when the system is at rest.

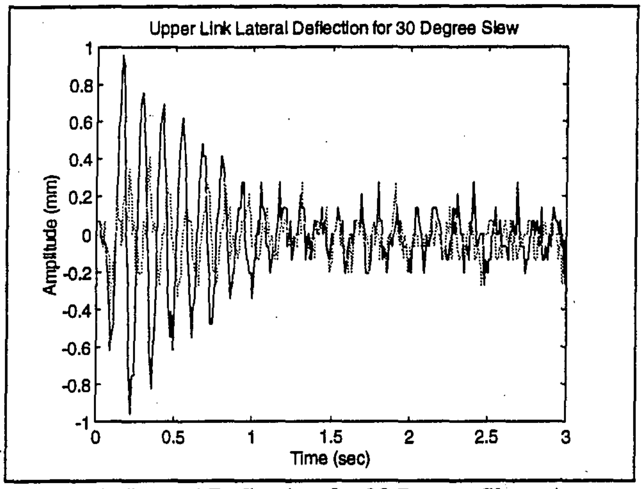

Figure 4. Lateral Deflection for 30 Degree Slew

An experiment was also run where the pitch joint is moved from 45 degrees to 0 degrees while the roll joints are again held at 0 degrees. Figure 5 demonstrates the effectiveness of the filtering algorithm to prevent flexible base vibration during the commanded wrist motion. The amplitude of vibration is again reduced by 60% over the nonfiltered PD case.

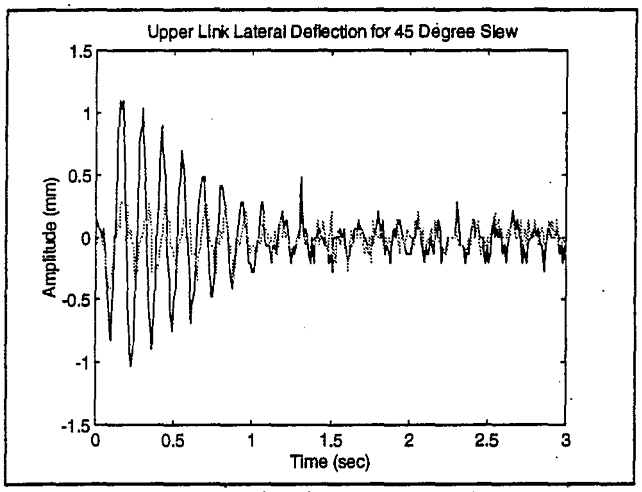

Figure 5. Lateral Deflection for 45 Degree Slew

V. Closing Remarks

A general filtering approach was presented that can produce both positive and negative input shapers (positive and negative filter coefficients) depending on the delay time value. This paper presented the limits for delay time and the effect on the magnitude of the filter's frequency response. It was shown that the filter can have delay times shorter than the conventional input shaping algorithm but will have as a consequence a frequency response magnitude greater than unity for some frequencies greater than the flexible natural frequency. This effect must be considered when designing a feedback control system that contains this new filter.

Experimental results confirmed the reduction in vibration that results from filtering in a PD joint control algorithm. The vibration amplitude was reduced by nearly 60% when the filtering method was used in the feedback control algorithm. Current research is investigating the effect of this filtering technique on the closed-loop poles of the system and how different delay times affect the overall stability.

VI. Acknowledgements

This research was partially supported through Sandia National Laboratories, Contract No. AK-9037.

VII. References

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